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**Improved Magnetostrictive Transducer Drive Elements  
Achieved by Reduction of Crystalline Defects and  
Improved Crystalline Orientation  
(Final Report)**

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## TABLE OF CONTENTS

		Page
	TITLE PAGE	
I.	INTRODUCTION	2
II.	BACKGROUND AND DEVELOPMENT	3
III.	RESEARCH PURPOSE AND TECHNICAL APPROACH	5
IV.	RESEARCH PLAN, TASK DESCRIPTIONS AND EXPECTED RESULTS	8
V.	RESEARCH TASK ACTIVITY, RESULTS AND DISCUSSION	13
VI.	SUMMARY AND FUTURE WORK	22

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## I. INTRODUCTION

The discovery of the "giant" magnetostrictive rare earth-iron alloys in the 1970's was a direct result of the efforts initiated at DOD's Naval Surface Warfare Center (NSWC), Silver Spring, MD in conjunction with DOE's Ames Laboratory (AL), Ames, IA. This research into these new materials was specifically targeted for the development of low frequency, high power transducers for underwater sonar systems.

The most technologically advanced of these materials in TERFENOL-D,  $\text{Tb}_{0.3}\text{Dy}_{0.7}\text{Fe}_{1.95}$ , an intermetallic compound consisting of iron (Fe) and the rare earth metals terbium (Tb) and dysprosium (Dy). Because of the advantages over existing transducer materials (see Table 1), the use of TERFENOL-D as a transducer drive element is expanding into a broad range of commercial applications and advanced defense systems. One of the disadvantages is the cost of these drivers, primarily the terbium and dysprosium raw materials. Two means of reducing these costs is to increase the performance which results in more output per unit volume and/or maintaining current performance levels using less pure (less expensive) rare earth metals. It is noteworthy that since 1990 the cost of the raw materials has declined by 45 percent as a result of ETREMA's procurement efforts. Through competitive pricing and volume purchases these costs are projected to be decreased by at least 47 percent below the current purchase prices. This research is directed toward improving the magnetostrictive properties of TERFENOL-D by reducing the crystalline defects in the material and obtaining the optimum  $\langle 111 \rangle$  crystallographic orientation with respect to the drive axis of these transducer elements. The myth that TERFENOL-D is expensive has been laid-to-rest and magnetostrictive transducer elements are becoming even more cost effective as the technology advances.

- Highest Strains of Commercial Driver Materials
- Highest Watt/Kilogram Figure of Merit  
(Results in greatly reduced weight and size)
- Capable of Continuous High-Power Performance
- High Force
- Coupling and Factor (Efficiency of Energy Conversion)  
Between 0.70 and 0.75
- Broad Frequency Response
- Sub-Micron Positioning Accuracy at High Stress Levels
- Wide Temperature Range - Cryogenic to 200 °C
- High Reliability - Long Life
- Low Voltage Power Input

Table 1. Advantages of ETREMA TERFENOL-D® Transducer Elements

To understand the full significance of this research we will briefly discuss the technologies with emphasis on the Navy's role in the discovery and development of these innovative "smart" materials. It should be noted that the U.S. involvement in the development of these TERFENOL-D technologies during the past five years has been far below that of our foreign competitors, in both the defense and commercial arenas. This is especially evident in the case of Japan where a huge sonar array using magnetostrictive transducers for ocean tomography applications is being developed under a JAMSTEC program (1). Several commercial applications developed in Japan, including magnetostrictive pumps for medical and vendor applications, linear motors, etc. were presented at the symposium cited (1).

In Sweden, ABB Seatech has developed a complete line of commercially available flextensional transducers based on TERFENOL-D. Although ETREMA TERFENOL-D® is used for the drive elements in these systems, it is ironic that the U.S. Navy is considering the purchase of one or more of these systems for test and characterization purposes. The point is, yet another technology that originated in the U.S. (DOD Navy) is being exported primarily because of lack of funding to complete the development in our country.

## II. BACKGROUND AND DEVELOPMENT

The intermetallic compound  $\text{TbFe}_2$  crystallizes in the cubic Laves phase (C15) structure and possesses the largest known room temperature magnetostriction, (theoretical strains in excess of 3000 ppm.) TERFENOL ( $\text{TbFe}_2$ ) is the generic name standing for (TER) terbium, (FE) iron and Naval Ordnance Laboratory (NOL) (now NSWC), where the materials were discovered.  $\text{TbFe}_2$  exhibits a huge magnetic anisotropy which inhibits easy domain rotation and results in an undesirable hysteretic behavior and large applied fields. By combining  $\text{TbFe}_2$  with  $\text{DyFe}_2$  which also possesses a large positive strain ( $\lambda$ ) but has an opposite sign of magnetic anisotropy, the anisotropy in the magnetization process can be compensated. The family of compounds  $\text{Tb}_x\text{Dy}_{1-x}\text{Fe}_2$  (TERFENOL-D), with  $x = 0.3$  being the most technologically developed, has been established and represent the materials being incorporated into many commercial devices and advanced defense systems.

TERFENOL-D exhibits a huge anisotropy in the magnetostriction ( $\lambda_{111} \gg \lambda_{100}$ ). This  $\lambda_{111}$  dominance accounts almost entirely for the "giant" magnetostriction in these compounds. Therefore, to achieve the highest magnetostriction it is necessary to produce these materials with their  $\langle 111 \rangle$  crystallographic direction near the drive axis of the transducer element.

Based on this information the ideal TERFENOL-D transducer drive element would be a defect-free single crystal with the  $\langle 111 \rangle$  crystallographic direction aligned along the drive axis. Currently, grain oriented and "single" crystal ETREMA TERFENOL-D® transducer drive elements are routinely produced and exhibit excellent strain values at low applied fields. Two crystal growth methods are used to produce these drivers. The free stand zone melt (FSZM) method yields the highest performance elements with dimensions 4-8 mm in diameter and 200 mm in length. This crystal growth method is described in the U.S. Patent 4,770,704 (2) and the magnetostrictive properties of these drive elements are reported (3-9).

For larger diameter 10-50 mm TERFENOL-D drive elements, a modified Bridgman method of crystal growth is used. This method is described in the U.S. Patent #4,770,704 (10) and the properties/ characterization of these drivers have been studied extensively (1,9,11-13). These studies focused primarily in connection with high power sonar transducers and applications that require high energy density drivers. Most of the improvements and developments of these larger diameter (10-50 mm) TERFENOL-D drive elements have occurred at ETREMA Products, Inc. which was established in 1987 as a "technology transfer" project to accomplish the commercialization of this technology.

Both of these crystal growth methods, free stand zone melt (FSZM) and MB, yield these magnetostrictive materials in rod shapes with the  $\langle 112 \rangle$  crystallographic direction oriented along the rod (drive) axis. The  $\langle 112 \rangle$  crystal growth is the result of a dendritic solidification of the alloy and is the natural growth direction for these cubic materials. It is characteristic of these dendrites to contain two or more parallel  $\{111\}$  twin planes along the center of the sheet dendrite plane. These twin boundaries are considered to be major crystalline defects (4,5) and their removal would result in the most significant improvement in the low field performance of these magnetostrictive materials (14).

Other crystalline defects that affect the magnetostrictive properties of TERFENOL-D are:

- 1) Impurities - either contained in the starting materials or introduced during the processing.
  - a) interstitial - oxygen, nitrogen, carbon
  - b) substitutional - aluminum, silicon
- 2) iron-rich phases, especially the  $R\text{Fe}_3$ , where  $R = (\text{Tb}_x\text{Dy}_{1-x})$ , which can occur either as a Widmanstatten precipitate in the TERFENOL-D ( $R\text{Fe}_2$ ) or as primary  $R\text{Fe}_3$  dendrites in the alloy matrix.
- 3) crystal structure stacking faults and edge dislocations

In essence any crystalline defects that inhibit magnetic domain motion must be minimized to realize the full low field magnetostriction in these TERFENOL-D transducer drive elements.

The basis for this contract research, as summarized in this section, resulted in the milestone chart shown in Figure 1. The technical objectives and research accomplishments are reported in this final report for this prematurely terminated (ONR funding cuts) research program.

### III. RESEARCH PURPOSE AND TECHNICAL APPROACH

The purpose of this research is to produce the "giant" magnetostrictive TERFENOL-D transducer elements in their most efficient form. Such components would be employed as transducer elements and advance the technology of smart structures.

The magnetization anisotropy in  $\text{TbFe}_2$  (TERFENOL) is compensated at the  $\text{Tb}_{0.3}\text{Dy}_{0.7}\text{Fe}_2$  (TERFENOL-D) stoichiometry. The anisotropy in the magnetostriction yields a maximum strain in the  $\langle 111 \rangle$  direction for these cubic Laves phase intermetallic compounds. Crystalline defects inhibit domain wall movement which leads to lower strains and higher hysteresis. The ideal TERFENOL-D transducer drive element would be a defect-free single crystal with the  $\langle 111 \rangle$  crystallographic direction oriented along the drive axis. The current technology routinely yields  $\langle 112 \rangle$  oriented crystals that exhibit excellent magnetostrictive properties.

These  $\langle 112 \rangle$  oriented crystals are the result of a dendritic growth and a characteristic of such cubic dendrites is the presence of twin boundaries down the center of each dendrite. Elimination of these twins would result in significant improvements in the practical and saturation strain capabilities in these TERFENOL-D drive elements. Twin free  $\langle 111 \rangle$  oriented crystals would yield even higher strains with less hysteresis in operation.

# Milestone Chart Months ARO

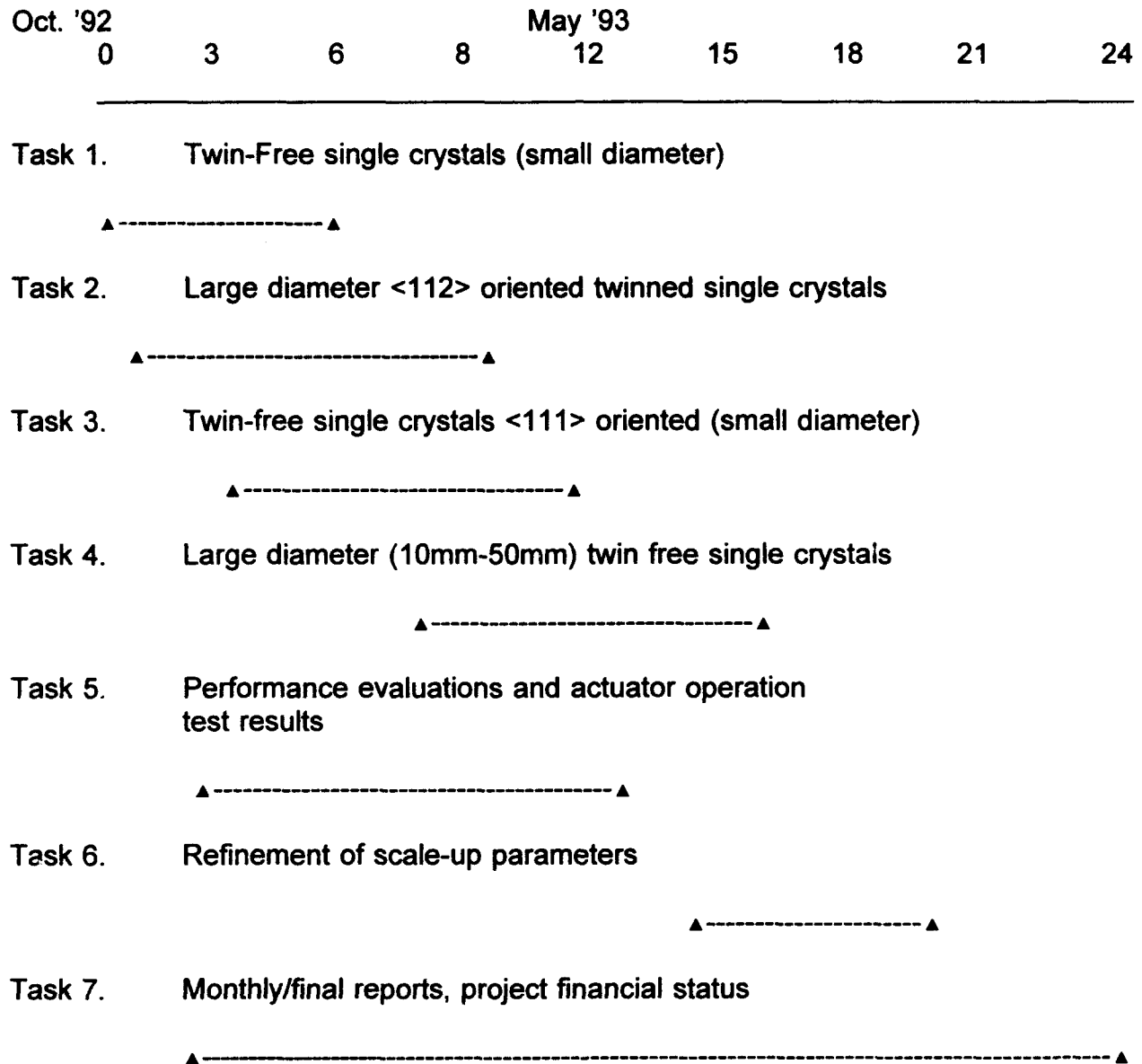


Figure 1. Milestone chart for original ONR contract. Funding cuts terminate work at 8 months ARO. All tasks are on schedule.

A float zone (containerless) crystal growth method would be researched initially. Seeding in non <112> directions is possible with this method and the growth interferences due to container impurity contaminations and nucleation sites are

eliminated. The factors that control the growth are the temperature gradient (G) and the rate (R). A high G/R ratio should yield non dendritic solidification and seeding with a  $\langle 111 \rangle$  direction crystal should yield a twin-free drive element. The vapor pressure of the alloy and slow growth rates may require this operation be done in a horizontal float zone system. The magnetostriction "jumps" observed in the twinned  $\langle 112 \rangle$  crystals should increase from 1000 ppm (H applied  $< 500$  Oe) to about 2000 ppm for the untwinned crystals. Strains approaching the 2440 ppm theoretical value should be obtained for the  $\langle 111 \rangle$  oriented twin free crystals at fields of about 2500 Oe. Figure 2 shows the magnetostriction "jumps" characteristic of the twinned  $\langle 112 \rangle$  crystals. The effect of prestress on the strain behavior is also shown in this plot (6).

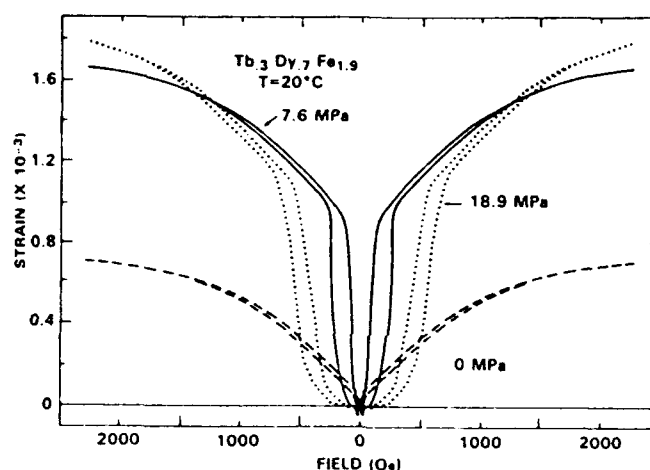


Figure 2. Magnetostriction of the  $\text{Tb}_{0.3}\text{Dy}_{0.7}\text{Fe}_{1.9}$  TERFENOL-D at 0, 7.6 and 18.9 MPa prestress. Low field magnetostrictive "jumps". Taken from Clark, et.al. (6).

The vertical float zone method is limited to rod diameters of 8-10mm. For drive elements with diameters between 10 and 50mm, a Bridgman crystal growth method is used. Multiple twinned  $\langle 112 \rangle$  crystals are observed in these larger diameter drive elements. The proposed research is planned to refine the growth parameters for these large diameter drive elements and produce them full length in a single or bicrystalline form. An increase of at least 20% in strain should result and the low field magnetostriction "jumps" should occur. Attachment of a seed chamber to the Bridgman crucible and control of the temperature gradient/solidification rate should produce these improved large diameter TERFENOL-D drive elements.



Large diameter, 10-50mm, TERFENOL-D drive elements that are twin-free are more difficult to produce due to the presence of a container. Crucible material contamination and the increased number of nucleation sites are the main source of these difficulties. However, twin free  $\langle 111 \rangle$  crystals of reasonable diameter are expected from these studies. Both the Bridgman and Czochralski crystal growth methods will be researched to attain these goals.

A complete evaluation of the magnetostrictive properties of all of the improved TERFENOL-D drive elements resulting from this research will be reported. The performance of full-scale actuators using these drive elements is included in this study. The process parameters required to scale to production levels will be established for these improved magnetostrictive TERFENOL-D transducer drive elements.

Technologies for Smart Structures are placing a rapidly expanding demand on the high force/high energy density properties of the "giant" magnetostrictive materials, TERFENOL-D. The improvements in these materials, as outlined in this research proposal, would make a significant contribution to the actuator/sensor technologies for all smart structures.

#### IV. RESEARCH PLAN, TASK DESCRIPTIONS AND EXPECTED RESULTS

The tasks listed in the milestone chart shown in Figure 1 are described along with the results expected from this research.

Task 1. Twin-free single crystals (small diameter)

Non  $\langle 112 \rangle$  oriented crystals that are free of major twin boundary defects. Small diameter (6 mm) produced by either a free-standing float zone solidification or horizontal levitation zone melt technique. The strain discontinuities/ magnetostriction "jumps" could be increased from the current 1000 ppm to about 2000 ppm.

Task 2. Large diameter  $\langle 112 \rangle$  oriented twinned single crystals.

Large diameter  $\langle 112 \rangle$  oriented single crystals produced by using seeding techniques in a Bridgman method. A 20% increase in the magnetostriction is expected.

Task 3. Twin-free single crystals  $\langle 111 \rangle$  oriented (small diameter).  $\langle 111 \rangle$  seeding and conditions established under Task 1 to obtain untwinned crystals with the  $\langle 111 \rangle$  direction along the drive axis of the transducer element. Nearly ideal drive elements that exhibit magnetostriction "jumps" of  $\approx 2000$  ppm at low fields ( $< 500$  Oe) and near saturation strains of 2400 ppm at applied fields of about

2000 Oe.

**Task 4.** Large diameter (10mm-50mm) twin-free single crystals.

Large diameter (10mm-50mm) drive elements that are twin-free. Expected to yield at least a 50% increase in the usable strain.

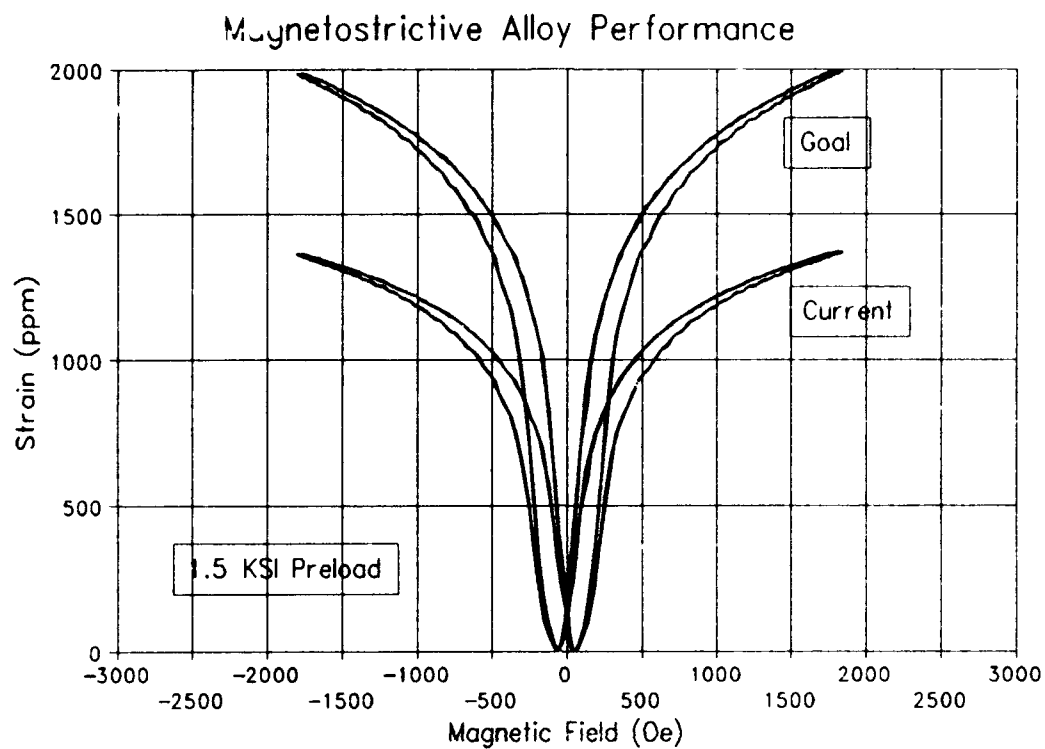
**Task 5.** Performance evaluations and actuator operation test results.

The magnetostrictive properties of these deliverables will be evaluated and their performance under established actuator operating conditions will be measured.

**Task 6.** Refinement of scale-up parameters.

Parameters determined during these process developments will be refined in order to make possible the scaling to production levels.

In summary the goal of this contract research is shown in Figure 3. The improvement in the magnetostrictive performance of these TERFENOL-D transducer drive elements to be achieved by the reduction of crystalline defects is shown in this strain ( $\lambda$ ) versus applied Field (H) plot. Higher strains at these fields are expected when the  $\langle 111 \rangle$  crystallographic alignment along the drive axis of the transducer element is achieved.



**Figure 3.** Performance of magnetostrictive TERFENOL-D transducer elements (current twinned <112> oriented crystals compared to research goals of defect-free <111> crystallographic oriented drive elements).

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## V. RESEARCH TASK ACTIVITY, RESULTS AND DISCUSSION

### Task 1. Twin-free single crystals (small diameters)

Crystal growth seeds were prepared by the free-standing zone melt (FSZM) process. The 175mm length of  $\langle 112 \rangle$  oriented seed material with a diameter of about 8mm was produced. A cross section of this seed rod is shown in Figure 4. The  $\langle 112 \rangle$  crystallographic direction is perpendicular to the plane of the paper and is the natural growth direction of these twinned TERFENOL-D sheet dendrites. The seeds for the non  $\langle 112 \rangle$  crystal growth experiments were cut from the seed rod. Crystal growth experiments were completed for the  $\langle 111 \rangle$  and  $\langle 110 \rangle$  crystallographic directions which are the principle directions perpendicular to the  $\langle 112 \rangle$  seed rods. The logic to these experiments stems from the fact that for most materials, including TERFENOL-D, the  $\langle 112 \rangle$  dendritic crystal growth invariably results in two or more twin planes in each sheet dendrite. By seeding in the non  $\langle 112 \rangle$  direction, such as  $\langle 111 \rangle$  perpendicular to the sheet dendrite, the formation of twin boundaries can be avoided and a major crystalline defect that restricts domain wall movement can be eliminated.

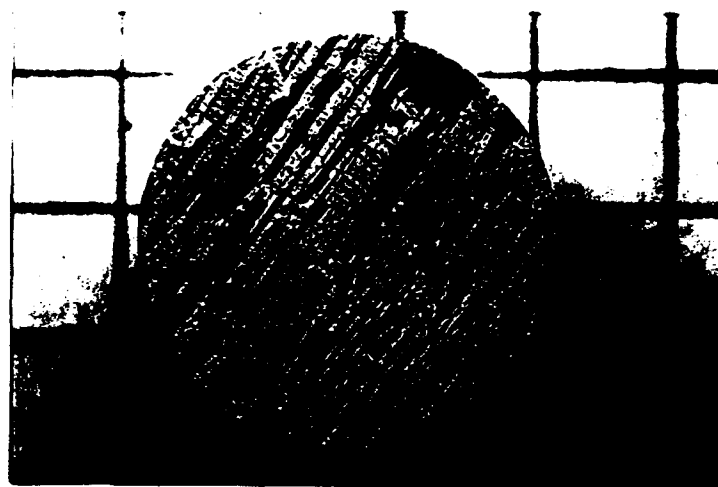


Figure 4. Cross section of FSZM TERFENOL-D showing sheet dendrites. The  $\langle 112 \rangle$  crystallographic direction is perpendicular to plane of paper. The  $\langle 111 \rangle$  crystallographic (seed) direction is perpendicular to the sheet dendrites in the plane of paper.



Figure 5. Longitudinal cross section of directionally solidified TERFENOL-D showing  $RFe_3$  - Widmanstatten precipitate, a crystalline defect, in the TERFENOL-D dendrites.

A series of 10 free-standing zone melt experiments with seeding in the  $\langle 111 \rangle$  direction was completed. The primary variables that determine the success of crystal growth are zone rate, temperature gradient and in the case of TERFENOL-D, the stoichiometry. The results are summarized in Table 2. The feed stock for these experiments was  $Tb_{0.3}Dy_{0.7}Fe_{1.95}$  and in some cases the  $RFe_3$  Widmanstatten precipitate was present in the  $RFe_2$  crystals (see Figure 5). Elimination of this phase and verification of the  $\langle 111 \rangle$  crystallographic orientation is necessary before the material can be used in Task 3. Although the performance of these crystals (See Figures 6 and 7) did not show improvement, the elimination of the twin boundaries as a defect has been accomplished. It is believed that the introduction of the  $RFe_3$  Widmanstatten precipitate has counteracted the effects of twin boundary removal and this was to be studied in Task 3. Elimination of both defects is expected to result in the 20%-50% improvement in strain proposed in this study.

Experiment	Zone Rate cm/hr	Comments
ONR-2-15	12	Dendritic growth
ONR-2-20	12	Initially non-dendritic, but dendritic at top. No $\text{RFe}_3$ , equi-axed grains 200/1000 micron in size. See performance curve in Figure 6.
ONR-2-25	3	Mostly non-dendritic growth. Fairly large equi-axed grains, but a lot of Widmanstätten $\text{RFe}_3$ present.
ONR-2-30	3.8	Mostly non-dendritic
ONR-2-35	0.4	Center section is non-dendritic and free of second phases. Edges of sample have R-Fe eutectic phase.
ONR-2-40	1.0	Mostly non-dendritic with eutectic phase on edges.
ONR-2-45	4.5	Non-dendritic on bottom, dendritic on top. See performance curve in Figure 7.
ONR-2-50	1.5	Non-dendritic growth. Short crystal used as seed in ONR-2-55.
ONR-2-55	1.5	All non-dendritic at start but could not maintain molten zone.
ONR-2-60	1.5	Same as ONR-2-55. Crystals from ONR-40,45,50,55 and 50 to be used in Task 3.

Table 2. Task 1 and Task 3 activity. Non-dendritic  $\langle 111 \rangle$  crystal growth to eliminate twin boundaries.



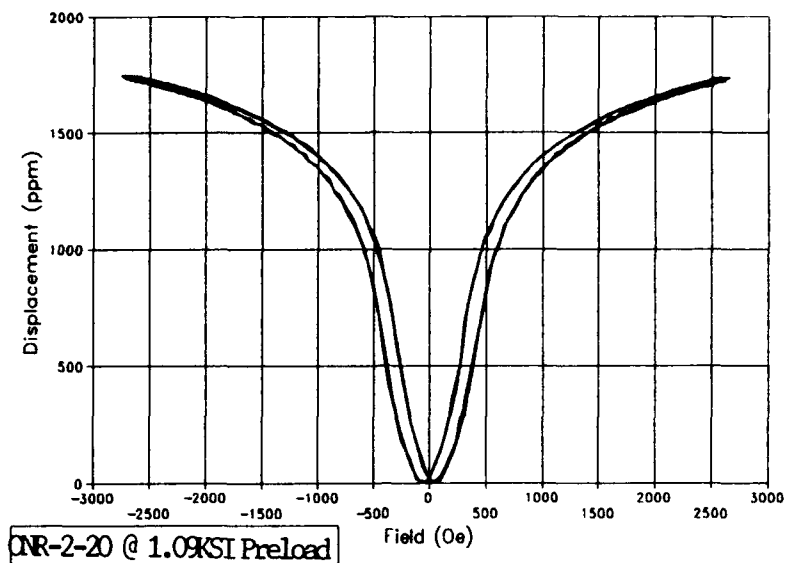


Figure 6. Strain ( $\lambda$ ) versus Applied Field (H) for FSZM TERFENOL-D with  $\langle 111 \rangle$  seeding. Non-dendritic growth at start and equi-axed grains.

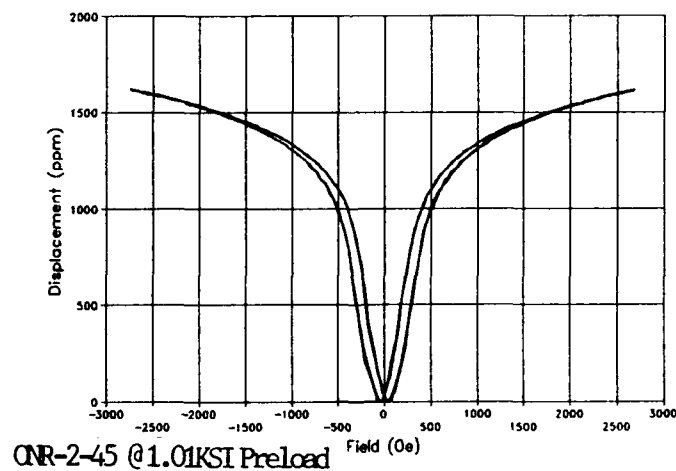


Figure 7. Strain ( $\lambda$ ) versus Applied Field (H) for FSZM TERFENOL-D with  $\langle 111 \rangle$  seeding. Initially non-dendritic growth showing no twins in this area.

The horizontal levitation zone melt (HLZM) method for crystal growth was used to produce twin free single crystals of TERFENOL-D. The object of these experiments was to produce crystals of sufficient size to use as seed materials in Task 3 of this research project. This method (HLZM) of crystal growth was successful in producing large single crystals of  $\text{TbFe}_2$  (see Figure 8) and  $\text{DyFe}_2$  that were used in the early developmental studies of TERFENOL-D magnetostrictive materials (15). The results of this Task 1 activity are summarized in Table 3. Twin-free single phase samples were obtained in most cases. The single crystals were generally small, except for ONR-1-115 where the crystals were large enough to serve as seeds for Task 3 activity. Slower zone rates improved the size of the crystals. The  $\text{RFe}_3$  phase in the form of Widmanstatten precipitate was observed in most of the  $\text{RFe}_{1.98}$  samples. The strain curve shown in Figure 9 exhibits below normal performance. However, the crystallographic alignment in this test sample is unknown and probably accounts for the low strain. The encouraging feature of this performance curve is the low hysteresis, which implies the absence of major defects and second phases as observed microscopically. More time and funding is needed to complete the characterization of these crystals especially in view of the success reported in the earlier study (15).

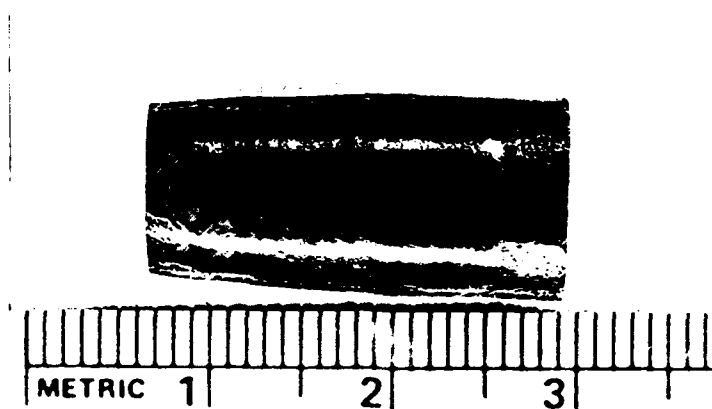


Figure 8. Single crystal of  $\text{TbFe}_2$  prepared by the horizontal levitation zone melt method (15). Crystal occupies space between 1 and 2.5 cm marks ( $\sim 1 \text{ cm}^3$ )

<u>SAMPLE No. ONR-</u>	<u>STOICHIOMETRY</u>	<u>ZONE RATE cm/hr.</u>	<u>RESULTS/COMMENTS Microscopic Observations of Cross Section</u>
1-40	$Tb_3Dy_7Fe_{1.95}$	1.3	two phase, several twinned crystals and primary $RFe_3$
1-50	$Tb_3Dy_7Fe_{1.95}$	3.8	single phase, several twinned crystals
1-60	$Tb_3Dy_7Fe_{1.95}$	3.3	single phase, twin free, small single crystals $\approx 2mm \times 4mm \times 10mm$
1-65	$Tb_3Dy_7Fe_{1.95}$	2.8	rezone of most of ONR-1-60, single phase, small twin free single crystals
1-80	$Tb_3Dy_7Fe_{1.98}$	4.0	twin free crystals, contained $RFe_3$ Widmanstatten ppt.
1-90	$Tb_3Dy_7Fe_{1.98}$	3.8	single phase, small single crystals
1-115	$Tb_3Dy_7Fe_{1.98}$	4.6 to 1.8	single crystals large enough to use as seeds for $\langle 111 \rangle$ crystal growth experiments
2-5	$Tb_3Dy_7Fe_{1.98}$	2.1	mostly single phase plus $RFe_3$ Widmanstatten ppt.
2-10	$Tb_3Dy_7Fe_{1.98}$	1.5	two phase

Table 3. Summary of results from crystal growth experiments using the Horizontal Levitation Zone Melt (HLZM) method. TASK 1 activity to produce twin free single crystals of TERFENOL-D magnetostrictive transducer materials.

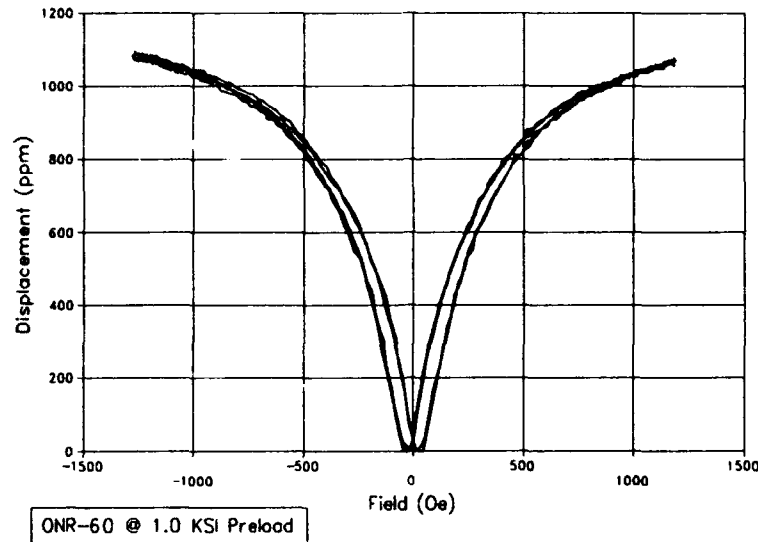


Figure 9. Strain ( $\lambda$ ) versus Applied Field (H) for non-heat treated single phase twin free sample of TERFENOL-D prepared by the Horizontal Levitation Zone Melt method. Demonstrates low hysteresis in material prepared by this method.

## Task 2. Large Diameter $\langle 112 \rangle$ Oriented Twinned Single Crystals

The purpose of this work is to determine the conditions needed to produce the large diameter (9-50mm) TERFENOL-D transducer drive elements with the same  $\langle 112 \rangle$  "single crystal" alignment obtained for the smaller diameter using the free-standing zone melt process (see Figure 4). This is expected to result in an increase in the usable strain of about 20% in these drive elements. The baseline strain of 1190 ppm at 1000 Oe with a prestress of 1 Ksi (7MPa) is used. The 20% improvement would increase the strain to 1425 ppm under these conditions.

These goals are to be accomplished by using seeded Bridgman crystal growth techniques. The TERFENOL-D stoichiometry was  $Tb_{0.3}Dy_{0.7}Fe_{1.92}$  in most cases and the feed stock rods resulted from a bottom pour operation that produces uniform diameter (9-50mm) polycrystalline rods in lengths up to 250mm.

Three different arrangements were used to melt the stock rods and each led to different liquid/solid interface conditions and temperature gradients and the solidification rate (pull rate) was varied according to these crystal growth conditions.

The first arrangement used a pancake RF concentrator coil to melt a narrow portion of the feed stock rod onto the seed material and then the (zoning) crystal growth was initiated. This produced a steeper temperature gradient conducive to crystal growth, but the excessive stirring of the melt disrupted the liquid/solid interface. Poor dendritic alignment and low performance resulted for the three samples (diameters 10-14mm) used in these experiments. The performance is shown in the strain ( $\lambda$ ) versus applied field (H) curve in Figure 10.

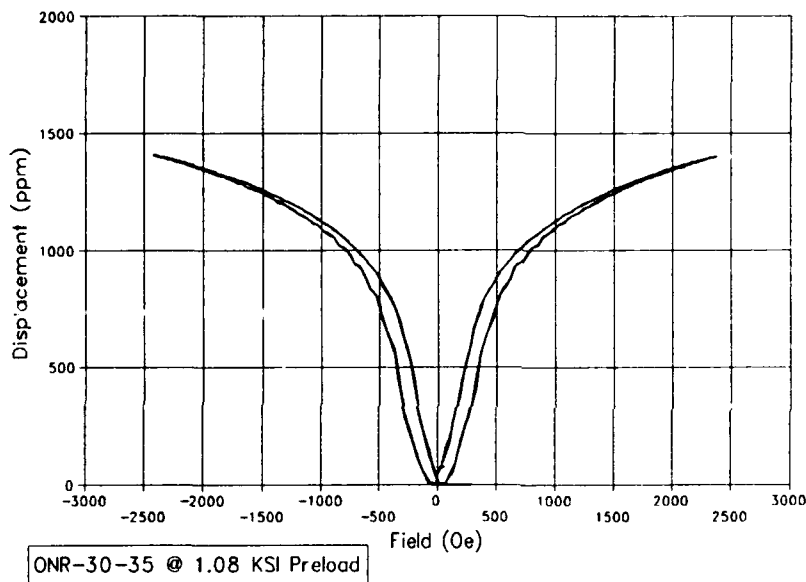


Figure 10. Seeded Bridgman crystal growth. Narrow molten zone produced by induction heating using a pancake coil arrangement. Excessive stirring disrupted liquid/solid interface and resulted in low performance drive elements.

The second arrangement used a solenoid induction heating coil and yielded improved performance. The 20% improvement was not achieved in this series of experiments but the number of crystals per cross section was reduced.

The improved strain levels of 20% (1190 ppm to 1425 ppm) were realized in these seeded Bridgman experiments when the induction heating was applied indirectly through a tantalum susceptor. The performance goal of Task 2 activity is shown in Figure 11. The number of crystals per cross section was reduced from 10 or more to 4 for these TERFENOL-D transducer elements. Additional experiments are needed to yield these drivers (9-50 mm diameter) in the "single crystal" form characteristic of the FSZM material shown in Figure 4.

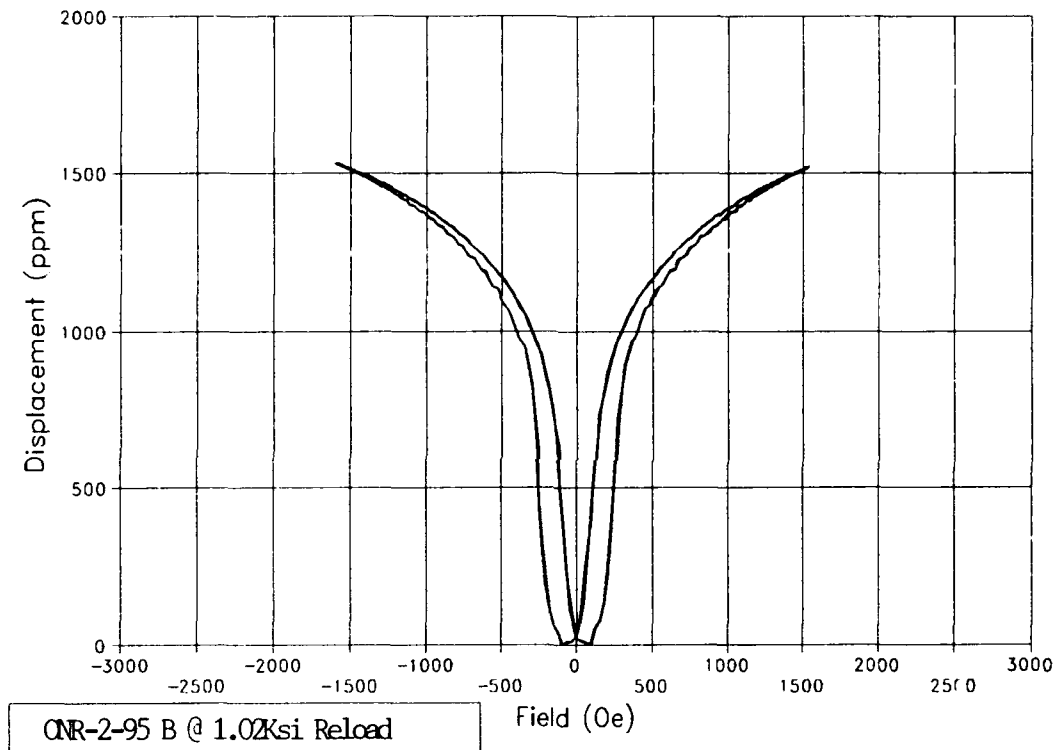


Figure 11. Strain ( $\lambda$ ) versus Field (H).  $\langle 112 \rangle$  Seeded Bridgman TERFENOL-D. 15mm  $\varnothing$  exhibiting a 20% increase in strain 1425 ppm at 1000 Oe.

Task 3. The preparation of twin-free single crystals with the  $\langle 111 \rangle$  crystallographic orientation along the drive axis was only initiated. The crystal growth seed materials from Task 1 were readied for this research work.

Task 4. Large diameter (10mm - 50mm) twin-free single crystals. Research scheduled but not initiated because of funding cuts.

Task 5. Performance evaluations and actuator operation test results.

All samples of this study were examined microscopically to determine the dendritic alignment, phases present, twin boundary population and single phase/single crystal nature. The performance of each TERFENOL-D driver obtained in the Task 1 and Task 2 work was measured in the form of strain ( $\lambda$ ) versus applied field (H) curves. These evaluations served as guidelines throughout these studies and established the success of these developmental efforts for the eight month period funded under this ONR contract.

Task 6. Refinement of scale-up parameters.

This task could not be initiated since it is dependent on the completion of Task 3 and Task 4. Funding for this contract research was cut and the planned work was curtailed in proportion.

## VI. SUMMARY AND FUTURE WORK

The work plan outlined in the Milestone Chart in Figure 1 shows the schedule for the planned Tasks of this research program. As reported in Section V all of the tasks were on schedule at the time of the program funding cut. The authorized funding allowed completion of the tasks through the eighth month (ARO) time period. The planned (proposed) improvements in the magnetostrictive properties of TERFENOL-D were accomplished (Task 1 and Task 2 activity). The  $\langle 111 \rangle$  crystallographic alignment of the transducer elements with respect to the drive axis was initiated in the Task 3 work. Completion of Task 3 work is expected to yield the optimum low field strain behavior for these transducer elements including reduced hysteretic character. The results to date are most encouraging that these major improvements would be accomplished.

Clearly additional funding is needed to complete this research program. This contract research is at the stage where each additional step will yield measurable progress toward the goal of high performance TERFENOL-D magnetostrictive transducer elements.

This developmental research is critical to the advancement of this DOD/DOE initiated technology. It is also essential to keeping pace with our foreign (especially Japan and Europe) competition in both the commercial applications and advanced defense related systems.

TERFENOL-D magnetostrictive materials and devices/systems using these materials represent a huge market. These technologies are a prime candidate for "dual use", and defense technology conversion, reinvestment programs. ETREMA Products was established for the purpose of transferring this technology from the government laboratories to the commercial sector. A worldwide customer base in 15 different fields as shown in Figure 12 has been established. ETREMA is positioned to complete this "technology transfer" and defense conversion, both of which will prevent the majority of these U.S. originated technologies from going to foreign countries. The need for government support remains and we respectfully request additional funding to complete this research contract.

## **ETREMA Products Inc.**

### **TERFENOL-D - MARKETS/CUSTOMERS**

**Commercial Applications**
**Aerospace Applications**

<b>Micro-Positioning/44</b>	<b>Petroleum Exploration/8</b>	<b>Sonar and Tomography/22</b>
<b>Active Antivibration/23</b>	<b>Sonic Data Transmission/7</b>	<b>Sensors/8</b>
<b>Vibrators &amp; Shakers/16</b>	<b>Machine Control High Force Pumps/8</b>	<b>Aircraft Control/2</b>
<b>Valve Controls/20</b>	<b>Motors- Linear and Rotary/7</b>	<b>High Force Actuators Fuel Injectors/7</b>
<b>Medical Sonics &amp; Hearing Aids/13</b>	<b>Smart Materials/15</b>	<b>Space Structure/7</b>

Figure 12. ETREMA Products customer base for magnetostrictive TERFENOL-D